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Physics Letters B 615 (2005) 160–166
PHYSICS LETTERS B
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Is the K-quantum number conserved in the order-to-chaos transition region?

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Received 29 June 2004; received in revised form 25 October 2004; accepted 9 December 2004

Available online 12 April 2005

Editor: V. Metag

Abstract

To study the order-to-chaos transition in nuclei we investigate the validity of the K-quantum number in the excited rapidly rotating ^{163}Er nucleus, analyzing the variance and covariance of the spectrum fluctuations of γ-cascades feeding into low-K and high-K bands. The data are compared to simulated spectra obtained using a microscopic cranked shell model. K-selection rules are found to be obeyed for decay along excited unresolved rotational bands of internal excitation energy up to around 1.2 MeV and angular momenta $20\hbar \leqslant I \leqslant 40\hbar$. At higher internal energy, from about 1.2 to 2.5 MeV, the selection rules are found to be only partially valid.

PACS: 21.10.Re; 21.60.-n; 23.20.Lv; 24.60.Lz; 25.70.Gh; 27.70.+q

Keywords: K-quantum number; Compound states; Excited rotating nuclei; Residual interaction; Quasi-continuum gamma spectra

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2004.12.083

The conditions under which K, the projection of aligned nucleonic angular momentum on the symmetry axis in deformed nuclei, is a good quantum number remain a topic of much current interest, as testified by the extensive experimental work on high-K isomers [1]. The study of nuclear states with high values of the K-quantum number is interesting not only from the point of view of the decay-out from such states but also in connection with their feeding, which allows to investigate the validity of the associated selection rules at higher internal excitation energies. As it was stated by Mottelson [2], the question of K-quantum number violation in excited states is a key issue in the study of the transition between ordered and chaotic motion in nuclei caused by the residual interaction and the high level density. In fact, as pointed out in Ref. [2], for a nuclear ordered system a complete set of single particle quantum numbers can be defined for each given state, resulting in selection rules on the associated electromagnetic transitions. On the contrary, in a chaotic regime, due to the complex nature of every state, no precise definition of quantum numbers (besides energy, spin and parity) is possible and selection rules lose their validity.

The issue of the validity of the K-quantum number has been previously addressed by studying the γ-decay from neutron resonances at excitation energy of ≈ 8 MeV [3,4]. In this Letter, we will focus on γ-transitions of quasi-continuum nature emitted by nuclei formed in fusion reactions, which are populating states at high spins (up to $I \approx 40\hbar$) and are probing the energy region extending up to excitation energy above yrast $U \approx 4$ MeV [5], with particular emphasis on the lower energy interval up to $U \approx 2.5$ MeV.

From theoretical investigations one expects that for $U \approx 1$–3 MeV a transition between order and chaos takes place. This has been studied, as usual, in terms of statistical fluctuations of the energy levels. It was found that, as the intrinsic excitation energy U increases, the level statistics shows a gradual transition from order-to-chaos, reaching at $U \approx 2.5$ MeV the Wigner distribution typical of the Gaussian orthogonal ensemble of random matrices [6,7]. Our investigation of selection rules can provide an experimental probe of this theoretical prediction. In fact, an experimental investigation based on level statistics is extremely hard at these excitation energies and spins, due to the rapidly increasing level density of interacting configurations. This differs from the case of low-spin neutron resonances, for which a Wigner level spacing distribution has been experimentally observed [8], and from the case of levels near yrast, which were found to follow the Poisson distribution typical of ordered systems [9].

The present work is based on new data on the ^{163}Er nucleus, which was already studied in a previous experiment [10]. Two novelties are presented. First, a more detailed experimental investigation is carried out for the highest region of internal energy. Secondly, and most important, a direct and rather realistic comparison between experiment and theory is made for the first time. This comparison is based on simulated spectra constructed using recent calculations on this specific nucleus [11].

The experiment was carried out using the EUROBALL array at the IReS Laboratory (France), employing the reaction $^{18}\mathrm{O} + {}^{150}\mathrm{Nd}$, at $E_{\mathrm{beam}} = 87, 93$ MeV. The ^{150}Nd target was made of a stack of two thin foils for a total thickness of 740 μg/cm^2. The corresponding maximum angular momentum reached in the reaction has been calculated to be $40\hbar$ and $45\hbar$ at the two bombarding energies, respectively. Energy-dependent time gates on the Ge time signals were used to suppress background from neutrons. A total of $\approx 3 \times 10^9$ events of triple and higher Ge-folds were finally obtained, with ^{162,163}Er as main evaporation residua. The data have been sorted into a number of two-dimensional (2D) matrices in coincidence with specific γ-transitions of ^{163}Er [12]. First, a matrix collecting the entire decay flow of ^{163}Er (named *total*) has been constructed by gating on the two cleanest low spin transitions. In addition, seven matrices gated by transitions belonging to the low-K ($K = 5/2$) signature and parity configurations labeled $A = (1/2, +)$, $B = (-1/2, +)$, $E = (1/2, -)$ and $F = (-1/2, -)$, and by the high-K ($K = 19/2$) bands labeled K1 (negative parity) and K2 and K4 (positive parity) [12] have been sorted together with their corresponding two-dimensional backgrounds. In addition, in order to perform a proper analysis of the 2D spectra in terms of statistical fluctuations [13], all known peak–peak and peak–background coincidences have been subtracted from each 2D spectrum using the Radware software [14]. Finally, the separately gated matrices have also been summed into one *low-K* ($A + B + E + F$) and one *high-K* (K1 + K2 + K4) matrix. Fig. 1 (left col-

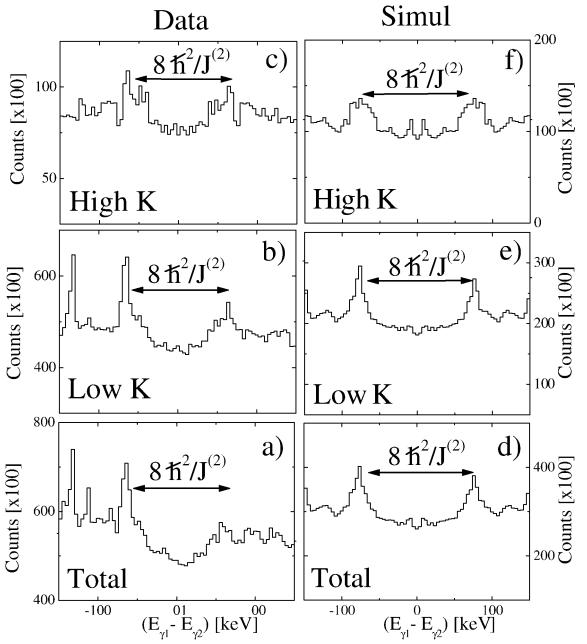

Fig. 1. 60 keV wide projections perpendicular to the $E_{\gamma_1} = E_{\gamma_2}$ diagonal of experimental and simulated 2D spectra of ^{163}Er (left and right panels, respectively), at the average transition energy $\langle E_\gamma \rangle = 900$ keV. The spectra collect either the total γ-decay flow (panels (a) and (d)) or the γ-decay in coincidence with low-K (panels (b) and (e)) or high-K (panels (c) and (f)) specific configurations. In the simulation, a state is defined as low-K (high-K) if $K \leqslant 8$ ($K > 8$). The ridge-valley structure typical of rotational nuclei is seen in all spectra, with a separation between the two most inner ridges equal to $8\hbar^2/J^{(2)}$, as indicated by the arrows. The reduced intensity observed in the $E_{\gamma_1} \geqslant E_{\gamma_2}$ region of the spectra is due to the subtraction of all discrete lines known from the level scheme, in the case of the experimental data, and of the yrast and first excited bands, in the case of the simulation.

umn) shows examples of cuts perpendicular to the $E_{\gamma_1} = E_{\gamma_2}$ diagonal, 60 keV wide, in the *total*, *low-K* and *high-K* γ–γ matrices, at the average transition energy $(E_{\gamma_1} + E_{\gamma_2})/2 = 900$ keV. As one can see, the spectra show the *ridge-valley* structure typical of quasi-continuum spectra of rotational nuclei, with a separation between the two most inner ridges equal to $8\hbar^2/J^{(2)}$, $J^{(2)}$ being the dynamical moment of inertia of the bands [13]. In particular, while the rather sharp ridges are due to the strong rotational correlations associated with the decay along discrete rotational bands up to ≈ 1 MeV excitation energy above yrast, the rather smooth central valley at $E_{\gamma_1} = E_{\gamma_2}$ mostly collects contributions from the more excited region of strongly interacting bands (rotational damping regime). The asymmetry observed in the intensity of the spectra is due to the discrete line subtraction, which is here made only for $E_{\gamma_1} \geqslant E_{\gamma_2}$.

Two experimental observables are used to determine the validity of the K-quantum number at increasing internal energy, namely, the number $N^{(2)}_{\text{path}}$ of decay paths measured in coincidence with low-K/high-K discrete bands and the r correlation coefficient [13,15]. While $N^{(2)}_{\text{path}}$ is related both to the level density and to the rotational damping width, r measures the similarity of the cascades recorded in coincidence with low-K or high-K bands. For example, a large value of r (≈ 1) indicates that many decay paths can lead both to low-K and high-K configurations, thus suggesting a weakening of the selection rules. Both $N^{(2)}_{\text{path}}$ and r can be obtained by a fluctuation analysis of γ–γ coincidence spectra. In the present case, the fluctuations of counts in each channel of the 2D matrices, expressed as variance and covariance, are evaluated by the program STATFIT [13] and stored into 2D spectra. Because each rotational E_γ-cascade on the average contributes one count in each $\frac{4\hbar^2}{J^{(2)}}$ interval, the statistical moments are evaluated over sectors of $\frac{4\hbar^2}{J^{(2)}} \times \frac{4\hbar^2}{J^{(2)}}$, corresponding to 60×60 keV intervals for rare earth nuclei around ^{163}Er.

From the fluctuation spectra we first extract the effective number of decay paths, which eventually feed into the gate-selected band. The number of decay paths $N^{(2)}_{\text{path}}$ having two γ-transitions with energies lying in a chosen 60×60 keV window in the γ–γ coincidence spectrum is obtained from the simple expression

$$N^{(2)}_{\text{path}} = \frac{N}{\mu_2/\mu_1 - 1} \times P^{(2)}, \tag{1}$$

where N is the number of events, while μ_1 and μ_2 are the first and second moments of the distribution of counts. The superscript (2) indicates that the extraction of the number of paths is based on first and second moments, while the $P^{(2)}$ factor corrects for the finite resolution of the detector system [13].

The number of paths obtained from the analysis of the first ridge of the 2D matrices gated by individual bands is found, in average, to be ≈ 10 for each of the four low-K and of the three high-K configurations. Adding together the number of paths relative to specific configurations, taking into account their rel-

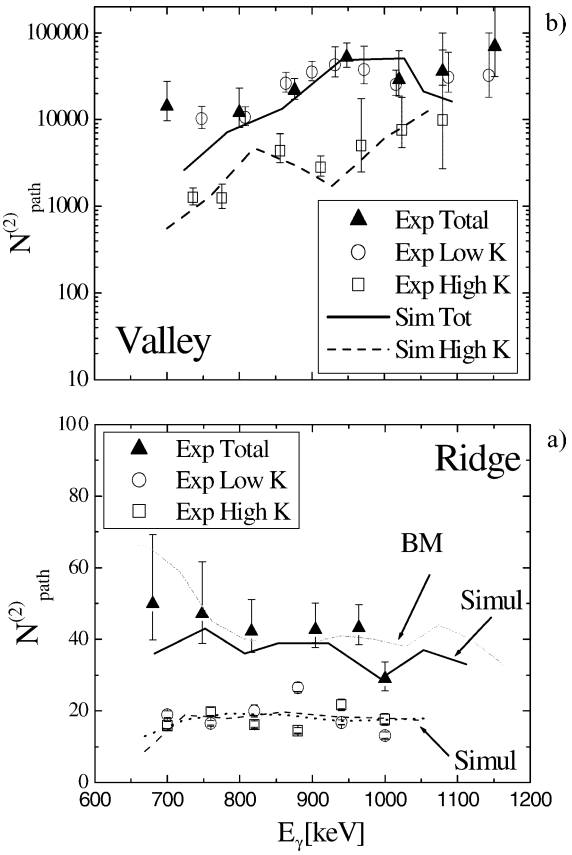

Fig. 2. (a) The number of decay paths extracted from the fluctuation analysis of the ridges structure of ^{163}Er. The open circles (squares) refer to the number of unresolved rotational bands populating the ridges of γ–γ matrices gated by low-K (high-K) configurations, while the full triangles give the number of discrete paths obtained from the total matrix. The corresponding values for simulated spectra are shown by dotted, dashed and full lines (low-K, high-K and total, respectively). The total number of discrete bands directly extracted from the bands mixing (BM) calculations is also given for comparison (thin solid line). (b) The effective number of transitions among mixed bands obtained from the fluctuation analysis of the valley region is shown by open circles (squares) for low-K (high-K) gated spectra, while the full triangles show the results obtained from the total γ–γ matrix. The dashed and solid lines give the theoretical expectations for total and high-K cascades, as obtained from simulated spectra.

ative intensities and correlations in a similar way as described in Ref. [15], a total number of ≈ 20 paths is found both for low-K and high-K states, as shown in Fig. 2(a) by open circles and squares, respectively. For the gates at the bottom of the bands, collecting the total decay flow, that is including both low-K and high-K bands, one finds that a total of ≈ 45 discrete rotational bands exist in the ^{163}Er nucleus, at internal energies below the onset of damping, as shown by triangles in Fig. 2(a).

In contrast to the results of the ridge analysis, the number of paths obtained from the valley region is found to depend significantly on the nuclear configuration for $E_\gamma \leqslant 1$ MeV. This result is shown in Fig. 2(b) together with the number of paths deduced from the total $E_{\gamma 1} \times E_{\gamma 2}$ spectrum. As the valley is probing the region in which the rotational bands are strongly mixed, this result intuitively suggests that the mixing process is indeed different for high-K and low-K states.

To provide a better understanding of the mixing of states with different K-quantum numbers we have studied the correlations between the fluctuations of the spectra gated on specific low-K and high-K bands. These correlations are expressed by the covariance of counts, defined as [15]

$$\mu_{2,\mathrm{cov}}(A,B) \equiv \frac{1}{N_{\mathrm{ch}}} \sum_j \big(M_j(A) - \tilde{M}_j(A)\big) \times \big(M_j(B) - \tilde{M}_j(B)\big), \quad (2)$$

where $M(A)$ and $M(B)$ refer to spectra gated by transitions from two different bands, A and B. The sum is over a region spanning N_{ch} channels (in this case 15×15) in a two-dimensional 60×60 keV window, and $\tilde{M}$ denotes an average spectrum (which in our case is obtained by the routine STATFIT as a numerical smoothed 3rd order approximation to the 2D spectrum). To normalize the covariance and thereby determine the degree of correlation between the two spectra, the correlation coefficient $r(A,B)$ is calculated:

$$r(A,B) \equiv \frac{\mu_{2,\mathrm{cov}}(A,B)}{\sqrt{(\mu_2(A) - \tilde{\mu}_1(A))(\mu_2(B) - \tilde{\mu}_1(B))}}. \quad (3)$$

Here, μ_2 denotes the second moment defined for the same region N_{ch}, related to the expression for the covariance by $\mu_2(A) = \mu_{2,\mathrm{cov}}(A,A)$. The first moment $\tilde{\mu}_1$ is the average of M over the region N_{ch}. The subtraction of the first moments in the denominator of Eq. (3) corrects for the contribution to μ_2 from counting statistics, which is linear in the number of events.

The more interesting fluctuations are due to the nature of the finite number of transitions available to each cascade, and their contribution to μ_2 is quadratic in the number of events.

Fig. 3 shows the average values of the correlation coefficient r extracted from the covariance analysis of the ridge and valley structures of γ–γ coincidence spectra of ^{163}Er. In each panel the solid lines indicate the two opposite limits expected in the case of a complete conservation of selection rules ($r = 0$) and of a compound nucleus regime ($r = 1$). In the case of the ridge analysis, r is found to be of the order of 0.2 for spectra gated on bands with similar low-K values (Fig. 3(a)), while it is approximately zero for combinations of low-K and high-K spectra (Fig. 3(b)). This shows that there are basically no cross-transitions between the ≈ 20 bands feeding high-K states and the ≈ 20 bands feeding low-K states. For the valley fluctuations, the correlation coefficient between low-K configurations is again of the order of 0.2. The r coefficient between low-K and high-K configurations, instead, increases from 0.2, at $E_\gamma \approx 700$ keV, up to $r \approx 0.5$ for $E_\gamma \approx 1$ MeV. Together with the fact that also the number of paths in the valley gated by low-K and high-K approaches each other, this represents an experimental indication of a weakening of selection rules associated with the K-quantum number with increasing rotational frequency and internal excitation energy.

To obtain further insights on the validity of the K-quantum number in excited states, we have performed simulations using band mixing calculations including both the residual interaction and a term that takes into account the angular momentum carried by the K-quantum number [11]. The calculations are made diagonalizing the Hamiltonian in a basis of np–nh excitations in a cranked Nilsson potential. The lowest eigenstates are retained, covering an interval above yrast of approximately 2.5 MeV. Inspecting the states resulting from the band mixing calculations, one finds that every state is characterized by a Gaussian distribution of K with a FWHM which is found to increase with U. Below $U \approx 1.5$ MeV the FWHM of the Gaussian distribution is found to be smaller than the typical spreading in the average value of K, so that it makes sense to define two different sets of states (i.e., low-K with $K \leqslant 8$ and high-K with $K > 8$), which turn out to correspond to level densities differing by a factor of ≈ 3. For $U \geqslant 2$–2.5 MeV the average value of K converges towards $\langle K \rangle \approx 7$ and the intrinsic FWHM is larger than the spreading in the average values. The distinction between low-K and high-K configurations is blurred, corresponding to the statistical limit of strong K-mixing. For energies around $U \approx 1.5$ MeV one finds an intermediate regime associated with the onset of K-mixing.

Starting from microscopically calculated bands, we have generated simulated γ–γ spectra by means of a Monte Carlo code [16,17] describing the competition between E2 collective and E1 statistical transitions, which cool the nucleus. While the E2 transitions are calculated microscopically, the statistical E1 transitions are obtained using the calculated level density and a GDR strength function corresponding to a prolate nucleus with quadrupole deformation $\beta = 0.25$ and rotating collectively. This β value coincides with the deformation parameter of the Nilsson potential used to produce the microscopic bands. In addition, an exponential quenching factor that takes into account the difference in K-quantum number between the initial and final states has been used in the simulation. Such a factor is analogous to the one employed in the analysis of the E1 decay-out from isomeric states [18,19].

Each γ-cascade is started from initial values of internal energy U and spin I randomly chosen from a two-dimensional entry distribution of Gaussian shape, with centroids and widths reproducing the experimental conditions (i.e., $\langle U \rangle = 4$ MeV, $FWHM_U = 4$ MeV, $\langle I \rangle = 44\hbar$, $FWHM_I = 20\hbar$). The resulting simulated intensities well reproduce the experimental values both for ridge structures and low spin yrast transitions.

The right column of Fig. 1 shows examples of 60 keV wide projections perpendicular to the $E_{\gamma_1} = E_{\gamma_2}$ diagonal of simulated γ–γ matrices collecting all cascades (total, panel (d)) and cascades finally feeding into low-K (panel (e)) and high-K (panel (f)) bands. The projections are taken at the average transition energy $(E_{\gamma 1} + E_{\gamma 2})/2 = 900$ keV, as in the corresponding experimental spectra (left column of Fig. 1). The asymmetry in the spectra is due to the subtraction of discrete lines which also in the simulated spectra is performed only for $E_{\gamma_1} \geqslant E_{\gamma_2}$. It is worth noticing that in the simulated matrices only the yrast and the first excited band (for each parity and signature con-

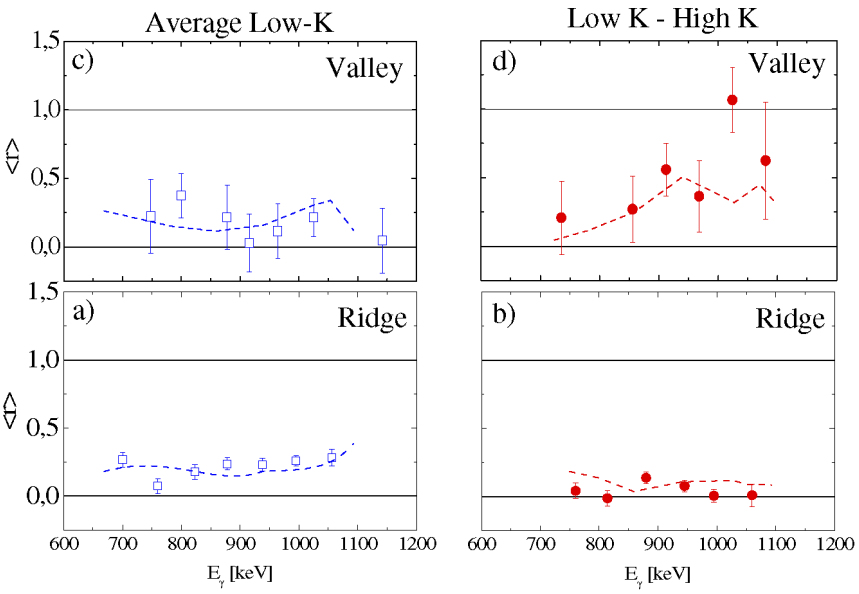

Fig. 3. The results of the covariance analysis on ridge (bottom panels) and valley (top panels) structures of ^{163}Er. Panels (a) and (c) show by open squares the correlation coefficient r obtained experimentally by averaging over pairs of γ–γ spectra gated by low-K configurations, while the correlation coefficient obtained from the experimental analysis of the *low*-K versus the *high*-K matrices is shown by full circles in panels (b) and (d). The theoretical values, as obtained from the covariance analysis of simulated spectra, are represented by dashed lines in all the panels.

figuration) have been subtracted, resulting in a more pronounced ridge than in the data, where all discrete transitions known from the level scheme have been removed.

The number of paths $N_{\text{path}}^{(2)}$ and the correlation coefficient r have been extracted from the simulated spectra using the same statistical analysis employed for the data, and the results obtained for the ridge and valley structures are shown with lines in Figs. 2 and 3. The results of the band mixing model are in good agreement with the data, both for the number of paths (Fig. 2) and the correlation coefficient (Fig. 3).

The number of paths in the ridge region corresponds to the total number of discrete bands which branch-out to less than 2 states [20] (shown by the thin solid line in Fig. 2(a)). This confirms that the nucleus ^{163}Er contains about 45 discrete bands at low internal energies before damping sets in [20]. Such number is higher than the typical 20 to 25 discrete bands obtained for ^{164,167,168}Yb [13,15], and can be attributed to the existence of the additional 20 high-K bands in ^{163}Er, which do not exist at such low energies in the other nuclei.

Turning now to the correlation coefficient in the ridge, the rather low value $r = 0.2$ obtained for the low-K versus low-K ridge analysis may be understood from the fact that at most two E1 transitions cool down the nucleus from the excited unresolved bands around $\langle U \rangle \approx 0.6$ MeV to the low-lying resolved bands. A simple quantitative estimate of the correlation coefficient can be deduced from the ratio between path probabilities, as described in Ref. [15]. In the case of bands with same parity and different signature, this path probability depends on the relative probability f for emitting an unstretched versus a stretched E1 transition, with $f \approx U^4/(U+\omega)^4$, being ω the rotational frequency. Altogether, for ridges including also bands with different parities, one obtains the simple expression $r = 2f/(1+f^2)$. Inserting now $U = 0.6$ MeV and $\omega = 0.4$ MeV, one finds $r \approx 0.25$. One may note that such small correlation coefficients support the specific choice of cooling transitions applied in the simulations. Thus, for example, an even competition between M1 and E1 transitions would lead to much higher correlation coefficients, which is excluded by the experimental results. The

combined effect of selection rules on E1s together with the straightforward parity-signature rules leads to a smaller value of r relative to the typical value $r \approx 0.2$. This is seen for simulations as well as data for low-K versus high-K ridge correlations.

Considering the r coefficient in the valley, a reasonable agreement between simulations and experimental data is generally found. In the case of low-K versus low-K the analysis gives a low value $r \approx 0.25$. This indicates similar probabilities for E1s crossing as found in the ridge, although one could expect, on the basis of the previous estimates, slightly higher values. The r coefficient between low-K and high-K tends instead to increase with E_γ, suggesting a progressive weakening of K-selection rules, due to the mixing of K-states. The flattening observed for $E_\gamma \geqslant 1$ MeV in the simulated coefficient between low-K and high-K is associated with the fact that the excitation energy of the γ-cascades at high spins extends up to values larger than the energy range covered by the simulated bands ($U \leqslant 2.5$ MeV).

From the fluctuation analysis in the valley (Fig. 2(b)), a clear difference in the number of paths $N_{\text{path}}^{(2)}$ between low-K and high-K gated spectra is seen up to $E_\gamma \approx 1$ MeV (i.e., $I \approx 38\hbar$ and $U \approx 2$ MeV), while the two quantities tend to converge at higher transition energies. This can be understood in terms of the onset of K-mixing, described above. In the lower energy region, not only the level density for high-K states is ≈ 3 times lower than for the low-K ones [11], but also the rotational damping width has been measured to be $\approx 30\%$ reduced for high-K states [21]. In schematic evaluations of the number of paths [13], the level density and the rotational damping width enter as quadratic terms, thus explaining roughly the factor of 10 separating the number of high-K and low-K gated paths.

In conclusion, we have discussed the onset of K-mixing in excited rapidly rotating nuclei by means of a comparison of results from high statistics experimental data on ^{163}Er with recently developed band mixing calculations for this specific nucleus. The experimental results from the fluctuation and covariance analysis on γ–γ coincidences address the region of spin $20\hbar$–$40\hbar$ and internal excitation energies up to around 2.5 MeV. For the lower interval of internal energy up to approximately 1.2 MeV, a rather strict conservation of the K-quantum number is found, as deduced by the analysis of the ridge structure which is formed by transitions along discrete unresolved bands. At higher internal energy ($1.2 \leqslant U \leqslant 2.5$ MeV), probed by the weaker and more numerous transitions forming the valley, a partial conservation of the K-quantum number is found, as shown by both the fluctuation and covariance analysis.

Further progress in the interesting topic of the order-to-chaos transition in nuclei will benefit from a better understanding of the internal excitation energy dependence of the K-mixing problem. For this purpose, future experiments focusing on high K-bands of larger internal energies are envisaged.

Acknowledgements

The work has been supported by the Italian Institute of Nuclear Physics, by the Danish Natural Science Foundation Research Council, by the Polish Committee for Scientific Research (KBN Grant No. 2 P03B 118 22), by EU Transnational Access to Major Research Infrastructures (Contract No. HPRI-CT-1999-00078) and by the EU TMR project (Contract No. ERBFMRXCT970123).

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